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Section 6

Risk Based Decision Process

I. INTRODUCTION

After the soil and water investigation phase is complete and the extent of contamination or the release has been quantified, the following questions must be answered:

- Does the residual soil and groundwater contamination pose a threat to current and/or probable future beneficial uses of water resources?
- Does the contamination pose an immediate or long-term threat to public safety, human health, or the environment, based on current or future site use?
- What levels of contamination remaining in the soil and/or groundwater would be acceptable without impacting public safety, human health, and the environment?
- Is remedial action technically and economically feasible, or can engineering and institutional controls be used to effectively mitigate the risks to human health and the environment from residual contamination?

The responsible party (RP) and the RP's consultant must evaluate answers to these questions. The regulatory agency will determine if the evaluation is adequate.

The following narrative provides guidance on identifying and evaluating the risks at a site and the framework for conducting risk-based corrective action. For more detailed description of the risk assessment process, please refer to the *Risk Assessment Guidance for Superfund* referenced below. The following are various documents that discuss risk-based corrective action.

- US-EPA, *Risk Assessment Guidance for Superfund (RAGS)*, December 1989, EPA/540/1-89/002 (use the most current update)
- US-EPA, *Region IX Preliminary Remediation Goals (PRGs)*, May 1998 (use the most current version of this document)
- Cal-EPA, Department of Toxic Substance Control, *Preliminary Endangerment Assessment Guidance Manual*, 1994
- American Society for Testing and Materials (ASTM), *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites*, (ASTM/RBCA) September 1995, E1739

In this document the term RBCA is the abbreviation for risk-based corrective action. This term is used as a generic description of the process and is not confined to the ASTM methodology.

Risks include health risk related to carcinogenic risk and acute and chronic non-carcinogenic risk, ecological risk, and the threat to water quality. For many chemical compounds, information about human health risk is available. Currently, information on short-term (acute) and long-term (chronic) risk to ecological receptors is limited. The following documents are common references for ecological receptors:

- US-EPA, *Quality Criteria for Water*, 1986 (also known as the "Gold Book")
- US-EPA, *Ambient Water Quality Criteria*, volumes on specific pollutants or classes of pollutants (1980, 1984, 1985, 1986, 1987, 1988, 1989, 1991, 1993, 1995, and 1998)
- US-EPA *Quality Criteria for Water*, 1976, (also known as the "Red Book")
- US-EPA *Water Quality Criteria*, 1972, (also known as the "Blue Book")
- Department of Toxic Substances Control (DTSC), *Guidance on Ecological Risk Assessments*, July 4, 1996
- US-EPA, *Framework for Ecological Risk Assessment*, 1992, (EPA/630/R-92/001)
- US-EPA, *Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessments: Interim Final*, 1997, (EPA 540-R-97-006)
- US-EPA, *Guidance for Ecological Risk Assessments*, 1998, (EPA/630/R-95/002Fa)

Acceptable levels of risk to human health can vary significantly based on site land use, adjacent land uses, and the perspective of the property owner, the occupant, and/or the public. An estimate of risk must include all pathways that apply to the conditions at a site. US-EPA indicated the acceptable carcinogenic risk could range from 1×10^{-4} to 1×10^{-6} with 1×10^{-6} being a level of de minimus risk (assumed to be insignificant risk). As a regulatory default, DEH considers 1×10^{-6} for both residential and commercial use, as the acceptable risk level. Due to the lack of clear guidance on acceptable exposure levels to ecological receptors, action levels will be developed on a case-by-case basis.

Risk requires three elements: a source, a pathway, and a receptor. If one of these is missing, no risk exists. If all three of these elements are present, a risk may exist. To pose a human health or ecological risk, the source of contaminants must be linked to the receptors by a complete pathway. A pathway is a route a contaminant takes to expose the receptor. Pathways may include natural pathways and man-made pathways. The possible transport media include the air (vapors and/or particulates), soil vapor, soil, sediment, and water (surface and ground).

II. WATER QUALITY OBJECTIVES

The California Regional Water Quality Control Boards (RWQCB) established water quality objectives for surface water and groundwater throughout California. These objectives are applied to sites where groundwater has been impacted, and they may be more restrictive than health based risk levels.

The Colorado River Basin RWQCB and the San Diego Basin RWQCB have established the water quality objectives in San Diego County as identified below:

A. Beneficial Use Waters

The beneficial use designations for both groundwater and surface water are presented in the following documents:

1. *Water Quality Control Plan for the Colorado River Basin (7)*, California Regional Water Quality Control Board, Colorado River Region, February 17, 1994
2. *Water Quality Control Plan for the San Diego Basin (9)*, California Regional Water Quality Control Board, San Diego Region, September 8, 1994

B. Non-Beneficial Use Waters

- **Colorado River RWQCB** – All basins identified in the Colorado River RWQCB Basin Plan for San Diego County are areas with designated beneficial uses.
- **San Diego RWQCB** - The San Diego RWQCB's Basin Plan identifies areas where groundwater has no designated beneficial uses. Cleanup levels in these areas will generally be defined by potential impacts to surface waters. The level of protection is based on the surface water beneficial uses, which will be established by the RWQCB on a case-by-case basis. Soil cleanups will be to a level that precludes the accumulation of non-aqueous phase liquid (NAPL) and ensures protection of human health and the environment. Removal of NAPL is the established groundwater remediation goal.

For sites within 1,000 feet of marine surface water, the San Diego RWQCB has issued interim cleanup goals for groundwater and criteria for mitigation of low-risk sites (April 1, 1996; revised July 23, 1996, [Appendix E.IV](#)).

III. RISK ASSESSMENT PROCESS

The completed evaluation of existing and potential risks at a site is called a “**risk assessment**.” A risk assessment may range from a very simple evaluation to an extremely complex evaluation including computer modeling.

A risk assessment consists of three major elements:

- Toxicity Assessment
- Exposure Assessment
- Risk Characterization

The following text is a detailed discussion of each of the three major elements with specific references to those sections of the manual that contain relevant guidance.

A. Toxicity Assessment

The purpose of the toxicity assessment is to characterize the relationship between the dose of the contaminant absorbed by an individual and the adverse consequences that may result.

Human health risks (carcinogenic and non-carcinogenic) are generally considered to be acceptable if the contaminant concentrations to which humans are exposed do not exceed health-based standards. The contaminant type and exposure route determine health-based standards. These standards include Applied Action Levels (AALs), Maximum Contaminant Levels (MCLs), and US-EPA Region IX Preliminary Remediation Goals (PRGs), and US-EPA Region III Risk Based Concentration (RBCs) and Reference Doses (RfDs). Health-based standards for carcinogens can be calculated from Cal-EPA and US-EPA cancer potency slope factors (SF). Health-based standards for non-carcinogens are calculated using Cal-EPA and US-EPA RfDs.

- The Cal-EPA cancer potency SF and RfD values can be obtained by contacting the Office of Environmental Health Assessment (OEHHA) of the Cal-EPA at (916) 324-2829.
- The US-EPA cancer potency SF values can be found in the US-EPA's Integrated Risk Information System (IRIS). Updates to US-EPA toxicity values can also be obtained from Health Effects Assessment Summary Table (HEAST), or the National Center for Environmental Assessment (NCEA).

Since the Cal-EPA cancer potency SFs are generally more stringent, the Cal-EPA SFs should be used.

For a quick reference, Table 6-1 provides the cancer SFs and RfDs for various compounds that are commonly encountered. Please be aware that these values may change with time. It is best to verify the most current values by contacting OEHHA and checking values in IRIS, HEAST, or NCEA.

The toxicity of an individual compound is typically established based on dose-response studies that estimate the relationship between different dose levels and the magnitude of their adverse effects. When evaluating exposures to multiple chemicals, preference is given to data on actual mixtures. Generally, the risks associated with individual constituents of a complex mixture are assumed to be additive and carcinogenic and non-carcinogenic risks are determined separately. For non-carcinogenic endpoints, it is appropriate to sum hazard quotients of compounds (hazard index) with similar toxicological endpoints and mechanisms of action.

Various chemical analysis methods such as for "Total Petroleum Hydrocarbons" (TPH) and "Total Volatile Hydrocarbons" (TVH) are often used during an initial site assessment to focus future investigations toward particular compounds and/or media. These measurements cannot be combined in a risk assessment because the general measure of TPH or TVH provides insufficient information about the amounts of individual compounds present to accurately characterize potential risk.

Carcinogenic

The primary index of cancer effects (i.e., quantitative expression of dose-response information) is the cancer potency SF. SF is a conservative estimate of the incremental probability of an individual developing cancer as a result of exposure over a lifetime. Another factor for carcinogens is the Weight of Evidence Class, which describes the quality and quantity of data that underlie their designation as a potential human carcinogen.

Non-Carcinogenic

The primary index of non-cancer effects (i.e., quantitative expression of dose-response information) is the hazard quotient for individual substances or the hazard index for multiple substances. The hazard index utilizes the reference dose (RfD), although reference concentrations (RfC) and acceptable daily intake (ADI) are also used. RfD is an estimate of the daily exposure to the human receptor that represents an acceptable risk of deleterious effects during a lifetime.

Ecological Receptors

Because current information regarding toxicity to ecological receptors is highly dependent on the environment, the ecological setting, and the species being protected, ecological receptors are evaluated on a case-by-case basis. An evaluation of ecological risk may involve input by DEH, RWQCB, US Coast Guard, US Army Corps of Engineers, California Department of Fish and Game and/or the US Fish and Wildlife Service.

TABLE 6-1
CANCER SLOPE FACTORS AND REFERENCE DOSES

CHEMICAL NAME	CAS #	Cancer SF 1/(milligrams per kilogram [mg/kg]- day)		RfD mg/kg-day	
		Oral	Inhalation	Oral	Inhalation
Benzene	71-43-2	1.0E-01 ¹	1.0E-01 ¹	3.0E-03 ²	1.7E-03 ²
Benzo(a)pyrene	50-32-8	1.2E+01 ¹	3.9E-00 ¹		
Carbon tetrachloride	56-23-5	1.5E-01 ¹	1.5E-01 ¹	7.0E-04 ²	7.0E-04 ²
Chlorobenzene	108-90-7			2.0E-02 ²	1.7E-02 ²
Chloroethane	75-00-3	2.9E-03 ²	2.9E-03 ²	4.0E-01 ²	2.9E-00 ²
Chloromethane	74-87-3	1.3E-02 ²	6.3E-03 ²		8.6E-02 ²
1,2-dichlorobenzene	95-50-1			9.0E-02 ²	5.7E-02 ²
1,3-dichlorobenzene	541-73-1			9.0E-04 ²	9.0E-04 ²
1,4-dichlorobenzene	106-46-7	5.4E-03 ¹	4.0E-02 ¹	3.0E-02 ²	2.3E-01 ²
1,1-dichloroethene (1,1-DCE)	75-35-4	6.0E-01 ²	1.8E-01 ²	9.0E-03 ²	9.0E-03 ²
1,1-dichloroethane (1,1-DCA)	75-34-3	5.7E-03 ¹	5.7E-03 ¹	1.0E-01 ²	1.4E-01 ²
1,2-dichloroethane (1,2-DCA)	107-06-2	4.7E-02 ¹	7.0E-02 ¹	3.0E-02 ²	1.4E-03 ²
Trans-1,2-dichloroethene	156-60-5			2.0E-02 ²	2.0E-02 ²
Dichloromethane	75-09-2	1.4E-02 ¹	3.5E-03 ¹	6.0E-02 ²	8.6E-01 ²
Ethylbenzene	100-41-4			1.0E-01 ²	2.9E-01 ²
Naphthalene	91-20-3			2.0E-02 ²	8.6E-04 ²
Methyl tertiary butyl ether (MTBE)	1634-04-4	1.8E-03 ¹	1.8E-03 ¹		8.6E-01 ²
1,1,1-trichloroethane	71-55-6			2.0E-02 ²	2.9E-01 ²
1,1,2-trichloroethane	79-00-5	7.2E-02 ¹	5.7E-02 ¹	4.0E-03 ²	4.0E-03 ²
Trichloroethene (TCE)	79-01-6	1.5E-02 ¹	1.0E-02 ¹	6.0E-03 ²	6.0E-03 ²
Trichloromethane	67-66-3	3.1E-02 ¹	1.9E-02 ¹	1.0E-02 ²	8.6E-05 ²
Tetrachloroethene (PCE)	127-18-4	5.1E-02 ¹	2.1E-02 ¹	1.0E-02 ²	1.1E-01 ²
Toluene	108-88-3			2.0E-01 ²	1.1E-01 ²
Vinyl chloride	75-01-4	2.7E-01 ¹	2.7E-01 ¹	3.0E-03 ²	2.9E-02 ²
Xylenes	1330-20-7			2.0E-00 ²	2.0E-01 ²

Note: ¹ Values listed are from Cal-EPA Office of Environmental Health Hazard Assessment, December, 2001

² Values listed are from US-EPA Region 9, PRGs, November 22, 2000

Exposure Assessment

An exposure assessment is a comprehensive evaluation of a site. This evaluation identifies all existing and potential exposure pathways. This may involve contamination caused by a single release or a collection of problems from on-site and/or off-site sources. There are three main components of an exposure assessment: a site assessment, pathway and receptor identification, and contaminant fate and transport evaluation. For additional guidance on site assessments refer to [Sections 4 and 5](#) of this manual.

1. Site Assessments

A complete site assessment adequately identifies the nature and extent of soil and groundwater contamination including its distribution, volume and mass. A complete site assessment must include the following information.

a. Chemical/Physical Properties of Contaminants

Determine the types, concentrations, and chemical/physical properties of individual contaminants and contaminant mixtures present at the site. These properties include, but are not limited to, aqueous solubility, vapor density, liquid density, cosolvency effects, organic carbon partition coefficient (K_{oc}), effective air diffusion coefficient (D_e), soil/water distribution coefficient (K_d), vapor pressure (VP), and Henry's Law Constant (H).

b. Contaminant Volume and Mass

Define the vertical and horizontal extent of soil and groundwater contamination. The distribution of contamination should be presented on maps and cross-sections. An estimate of the contaminant concentration, matrix mass, and volume must be provided.

c. Site Geology and Hydrogeology

Confirm the site geology and hydrogeology by field observation during drilling or excavation work at the site. The site geology must be interpreted in the context of regional geology. Soils must be described by using the accepted standards of the Unified Soil Classification System for soils. Descriptions must be consistent with the generally accepted geological classification of rocks. Please refer to [Section 5.III](#) for more detailed description of soil and rock classification.

d. Model Input Parameters

Use site-specific data as input for the most sensitive parameters in the fate and transport model. A sensitivity analysis should be conducted to identify the critical data required. Collection of the most sensitive data during the site assessment phase is recommended to minimize investigation costs incurred during multiple equipment mobilizations.

All physical and chemical analyses must be performed in accordance with documented and approved test methods (US-EPA, ASTM, Cal-EPA, etc.). The site-specific data required for input into fate and transport models vary depending on the model used. Models may use one or more of the parameters listed below. Not all parameters are necessary, but those used must be justified.

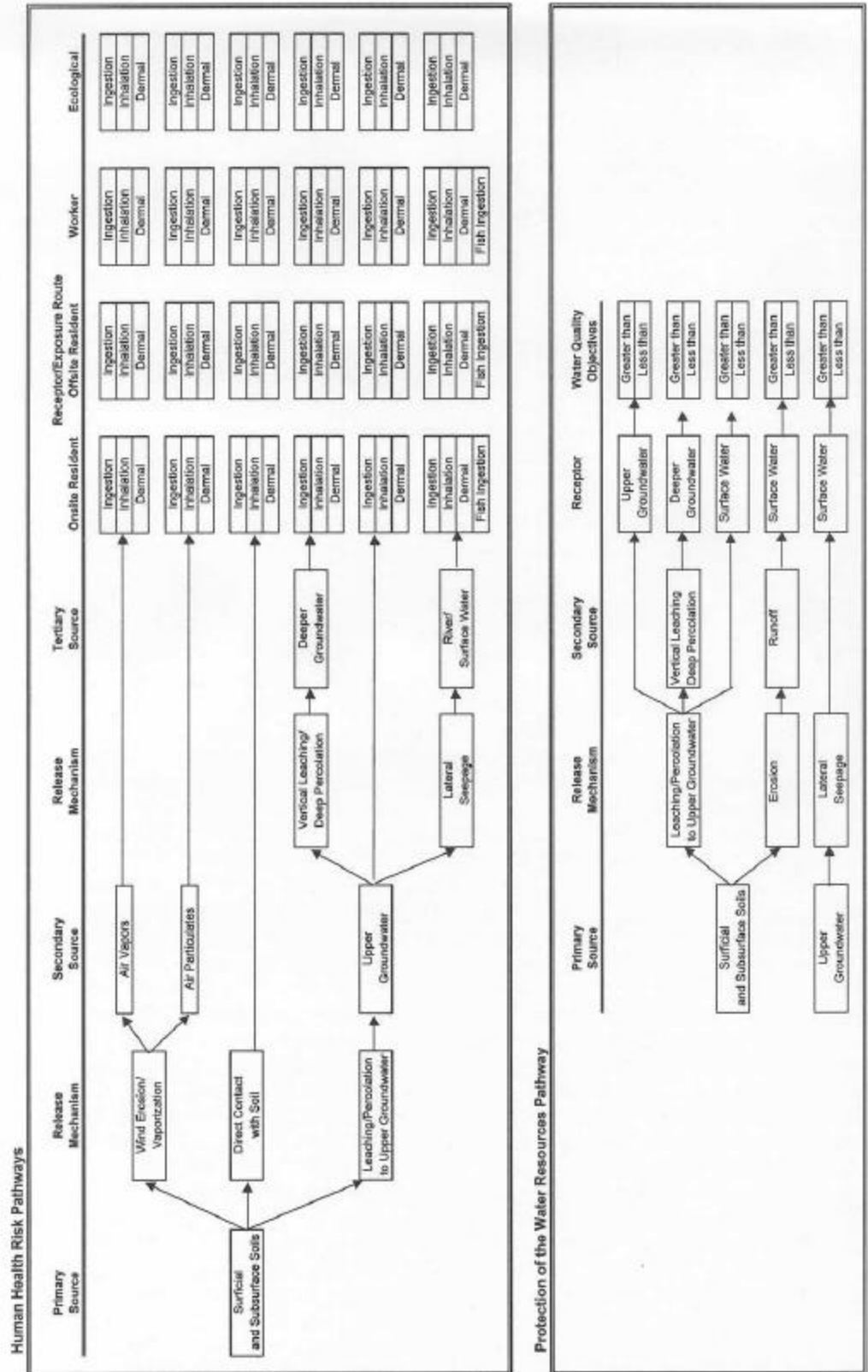
- Soil bulk density
- Soil particle density
- Soil moisture content
- Organic carbon content
- Soil porosity
- Unsaturated vertical and saturated horizontal hydraulic conductivity and transmissivity
- Soil suction, matric potential, capillary suction
- pH and redox potential
- Soil cation and anion exchange capacities
- Laboratory grain-particle size analysis
- Stratigraphic sequence and spatial distribution of geologic materials (soils and rocks)
- Identification and analysis of fractures and faults in the subsurface, including analysis of fracture orientation and density at the site
- Site topography and ground surface conditions
- Depth to groundwater (current and historic water level fluctuations, tidal fluctuations, locations of recharge and discharge areas, and groundwater flow directions and gradients)
- Distance to receptors (e.g., human, environmental, surface water, groundwater, utilities, adjacent properties)
- Annual climatic variables (e.g., annual rainfall, rainfall intensities, storm frequency, temperature, evapotranspiration)

2. Pathway and Receptor Identification

There are many ways a contaminant may reach a receptor. A receptor may include humans, plants, animals, man-made structures, surface water, and/or groundwater resources. It is also important to consider the probability of a foreseeable land use change that may result in a future exposure to a receptor.

The first step in evaluating exposure pathways is to identify those pathways that are relevant to the conditions at the site. The first step in a pathway analysis is development of a site conceptual model in accordance with the example provided in [Figure 6-1](#). In order to formulate a realistic and representative conceptual model and begin the fate and transport modeling process, a comprehensive site assessment must be completed.

FIGURE 6-1
SITE CONCEPTUAL MODEL



The exposure of a receptor to environmental contamination requires a pathway for the contaminant to travel to the receptor. Typical pathways for contaminated sites include:

- Non-aqueous phase liquid (NAPL) migration from source area into structures, utilities, surface water, and/or groundwater
- Vapor migration from soil, groundwater or NAPL into structures, utilities, and/or ambient air
- Solute migration from source area to a receptor (well, surface water, groundwater, etc.)

For humans and animals, exposure usually occurs by the following typical exposure routes:

- Ingestion of contaminated drinking water
- Inhalation of vapors from contaminated drinking water
- Inhalation of vapor from contaminated soil or groundwater
- Ingestion or inhalation of contaminated soil particles
- Dermal contact with contaminated soil particles

In areas where the groundwater and /or surface water are considered to be a receptor, the following are typical pathways that may apply:

- NAPL migration from source area into surface water and/or groundwater
- Solute migration from source area to surface water and/or groundwater

3. Contaminant Fate and Transport

Fate and transport analyses are procedures used to assess the mobility, migration potential, and persistence of contaminants in the environment. Due to the complexity of contaminant migration, computer simulations (models) are commonly used to estimate a contaminant's environmental fate and transport. Many different models are available. The user must have a thorough knowledge of the model's limitations and assumptions, and ensure that the model is appropriate for the conditions of the site being modeled. The approach and calculations presented in the following are limited to non-fractured geologic environments.

Fate and transport models are designed to provide a method to objectively estimate the effects of natural processes on the stability and the distribution of contaminants in the environment. The variability of geologic materials and/or the interactions between natural processes can be very complex. For this reason, fate and transport models must include many simplifying assumptions.

Therefore, the model results are treated as "estimates" rather than absolute "answers." The reliability of the "estimate" is directly linked to the validity of the input parameters to accurately simulate conditions at the site.

Fate and transport modeling may be used at several points in the corrective action process.

4. Discussion with Regulatory Agencies

Prior to the initiation of a fate and transport-modeling program, the RP and consultant should meet with the lead agency to discuss the appropriate level of effort required to evaluate a site.

It must be demonstrated that the chosen model(s) can adequately simulate the conditions of the site such that the conclusions drawn from the model(s) will be considered valid. The regulatory agencies reserve the right to decide whether a site is appropriate for a fate and transport modeling approach.

5. Level of Evaluation

DEH recommends a phased approach to the fate and transport modeling as it relates to the risk assessment process. For some sites modeling may not be appropriate. The use of regulatory guidance such as PRGs or other values provided by DEH or RWQCB may be more appropriate when the resulting cleanup volume and cost would be small. However, if the impact is significant, it may be appropriate to consider simple models such as those presented in this chapter for evaluating risk due to vapor and solute movement.

In general, DEH recommends the use of the simplified fate and transport methods and calculations presented below. The four main pathways that a contaminant may reach a receptor are:

- NAPL Migration in Soil
- Leaching and Migration in Soil
- Vapor-Phase Migration
- Groundwater Contaminant Transport (to receptors, surface water)*

* Note: In areas where groundwater is designated as having beneficial uses, the RWQCB considers the groundwater a receptor and the water quality objectives are MCLs.

For each pathway section there are three levels of evaluation provided.

- **Level 1 Evaluation** – This level of evaluation requires the use of minimal site-specific data. The use of conservative default values in the analytical models provided in the following sections will provide conservative estimates of the potential concentrations at the point of exposure. Typical default values are provided in **Tables 6-2 through 6-4**.
- **Level 2 Evaluation** – This level of evaluation requires the use of more site-specific data in the analytical model provided. Commonly, the site-specific data used are the most sensitive in the analytical model provided. This approach will generally provide conservative estimates of the potential concentrations at the point of exposure.
- **Level 3 Evaluation** – This level of evaluation requires the use of site-specific data in addition to more complex modeling programs. The most sophisticated approach may include multiphase numerical models based on detailed site-specific data. Only well-documented models that have been scientifically peer reviewed and validated should be used. DEH and the RWQCB may request copies of the model and model documentation.

6. Input Variables

Sections 6.III.7 through 6.III.9 provide simplified analytical equations to describe a contaminant's environmental fate and transport in the subsurface. For quick reference, the following list of terms is provided:

A	=	the room floor area (m^2)
A_v	=	the area of infiltration (cm^2)
C_f	=	the final concentration in soil pore water at water table (ug/l)
C_i	=	the indoor air concentration (mg/m^3)
C_s	=	the concentration of compound in soil (mg/kg)
$C_{s(TPH)}$	=	the concentration of TPH in soil (mg/kg)
C_{gw}	=	the calculated concentration in groundwater (ug/l)
C_w	=	the concentration in soil pore water (ug/l)
C_{sg}	=	the contaminant concentration in the soil vapor (mg/m^3)
d	=	the depth of groundwater mixing zone (cm)
D_a	=	the diffusion coefficient of compound in air (cm^2/sec)
D_e	=	the effective air diffusion coefficient (cm^2/sec)
D_f	=	the dilution factor (dimensionless)
E	=	the indoor air exchange rate per hour (air exchanges/hr)
Fx	=	the contaminant vapor flux ($mg/hr-m^2$)
f_{oc}	=	the weight fraction of organic carbon in soil = $TOC/10,000$
H	=	the Henry's Law Constant (dimensionless)
i	=	the gradient (dimensionless)
K	=	the saturated hydraulic conductivity (cm/sec)
K_{avg}	=	the average vertical hydraulic conductivity (cm/sec)
K_d	=	the soil/water distribution coefficient (cm^3/gm)
K_{oc}	=	the organic carbon partitioning coefficient (cm^3/gm)
K_{swz}	=	the vertical saturated hydraulic conductivity of the soil (cm/sec)
L	=	the distance of travel (cm)
MF	=	the mole fraction (dimensionless)
MW	=	the molecular weight of the compound of concern (mg/mole)
$MW_{(TPH)}$	=	the molecular weight of TPH (mg/mole)
q_z	=	the darcy velocity (cm/sec)
Q_{gw}	=	the unit mass flux of groundwater (cm^3/sec)
R	=	the universal gas constant ($atm-m^3/mole-K$)
Rh	=	the room height (m)
S	=	the pure component aqueous solubility ($mg/l-H_2O$)
Sb	=	the slab attenuation factor (dimensionless)
SF	=	the contaminant carcinogenic slope factor ($[mg/kg-day]^{-1}$)
S_r	=	the specific retention (dimensionless)
S_y	=	the specific yield (dimensionless)
T	=	the temperature in degrees Kelvin ($^{\circ}K$)
T_c	=	the time to reach groundwater (sec)
$t_{1/2}$	=	the biodegradation half life of contaminant (sec)
TOC	=	the total organic carbon content (mg/kg)
v	=	the infiltration velocity (cm/sec)
V	=	the room volume (m^3)
VP	=	the contaminant vapor pressure at STP (atm)
X	=	the depth or distance to contamination in the vadose zone (m)
Z	=	the gravitation component (cm)

ρ_b	=	the dry bulk density of soil (gm/cm ³)
θ	=	the total soil porosity (dimensionless)
θ_a	=	the air filled porosity (dimensionless)
θ_w	=	the water filled porosity (dimensionless)
Ψ	=	the capillary suction component (cm)

Tables 6-2a and 6-2b are provided to summarize the chemical properties of the most common chemicals encountered. Table 6-3 provides typical ranges of soil properties that are found in San Diego County. Table 6-4 lists conservative default values for various physical properties.

	Mol. Wgt mg/mole	Specific Gravity gm/cm ³ (T)	Boiling Point C	Vapor Pressure atm	Viscosity cP(T)	Solubility mg/l-H ₂ O(T)	Henry's Law Constant (dim-less)	Da cm ² /sec	Koc cm ³ /gm
benzene	78,110	0.8787 (15)	80	1.3E-01 (20)	0.6468 (20)	1,800	2.3E-01	8.8E-02	6.2E+01
benzo(a)pyrene	252,300	1.3510 (20)	>360	1.3E-03 (20)		0.00162	4.6E-05	4.3E-02	1.0E+06
carbon tetrachloride	153,840	1.5940 (20)	76.54	1.2E-01 (20)	0.9690 (20)	790	1.2E+00	7.8E-02	1.5E+02
chlorobenzene	112,560	1.1058 (20)	132	1.6E-02 (25)	0.7900 (21)	470	1.5E-01	7.3E-02	2.2E+02
chloroethane (ethyl chloride)	64,520	0.9214 (0)	12	1.3E+00 (20)	0.2790 (10)	5,700	4.5E-01	1.0E-01	1.5E+01
chloromethane (methyl chloride)	50,490	0.9159 (20)	-23.7	5.7E+00 (25)	0.1834 (20)	8,200	9.8E-01	1.1E-01	3.5E+01
1,2-dichlorobenzene	147,010	1.3059 (20)	180.5	1.9E-03 (25)	1.3240 (25)	160	7.8E-02	6.9E-02	3.8E+02
1,3-dichlorobenzene	147,010	1.2880 (20)	172	2.8E-03 (25)	1.0450 (23)	160	7.8E-02	6.9E-02	3.8E+02
1,4-dichlorobenzene	147,010	1.2480 (55)	174	1.3E-03 (25)	0.6680 (26)	74	1.0E-01	6.9E-02	6.2E+02
1,1-dichloroethene (1,1-DCE)	96,940	1.2129 (20)	31.7	7.8E-01 (25)	0.3302 (20)	2,300	1.1E+00	9.0E-02	6.5E+01
trans-1,2-dichloroethene	96,950	1.2700 (25)	48	5.2E-01 (30)	0.4100 (20)	6,300	3.8E-01	7.1E-02	3.8E+01
1,1-dichloroethane (1,1-DCA)	98,970	1.1740 (20)	57.3	2.5E-01 (20)	0.3770 (20)	5,100	2.3E-01	7.4E-02	5.3E+01
1,2-dichloroethane (1,2-DCA)	98,960	1.2600 (20)	83.5	8.0E-02 (20)	0.8400 (20)	8,500	4.0E-02	1.0E-01	3.8E+01
dichloromethane (methylene chloride)	84,900	1.3300 (15)	40	5.3E-01 (24)	0.4490 (15)	13,000	9.0E-02	1.0E-01	1.0E+01
ethylbenzene	106,000	0.8626 (25)	136	1.5E-02 (26)	0.6400 (25)	170	3.2E-01	7.5E-02	2.0E+02
naphthalene	128,200	1.1450 (20)	218	3.0E-04 (20)	0.9670 (80)	31	2.0E-02	5.9E-02	1.2E+03
methyl tertiary butyl ether (MTBE)	88,150	0.7405 (20)	55	3.2E-01 (25)		48,000	2.4E-02	8.0E-02	7.8E+02
tetrachloroethene (PCE)	166,000	1.6230 (20)	121	1.9E-02 (20)	0.8390 (25)	200	7.5E-01	7.2E-02	2.7E+02
toluene	92,150	0.8660 (20)	110.6	3.7E-02 (20)	0.5900 (20)	530	2.7E-01	8.7E-02	1.4E+02
1,1,1-trichloroethane	133,420	1.3376 (20)	75	1.3E-01 (25)	0.8580 (20)	1,300	7.1E-01	7.8E-02	1.4E+02
1,1,2-trichloroethane	133,000	1.4416 (20)	114	2.5E-02 (20)	1.6900 (25)	4,400	3.7E-02	7.8E-02	7.5E+01
trichloroethene (TCE)	131,400	1.4649 (20)	87	7.6E-02 (20)	0.5500 (25)	1,100	4.2E-01	7.9E-02	9.4E+01
trichloromethane (chloroform)	119,000	1.4840 (20)	61	2.8E-01 (25)	0.0563 (20)	7,900	1.5E-01	1.0E-01	5.3E+01
vinyl chloride	62,500	0.9106 (20)	-13.37	3.5E+00 (20)	0.0107 (20)	2,800	1.1E+00	1.1E-01	1.9E+01
xylene (average)	106,160	0.8640 (20)	137	1.1E-02 (25)	0.6927 (20)	180	2.7E-01	7.8E-02	2.5E+02

¹ Genium Publishing Corp, Materials Safety Data Sheets

² TOMES, 1998, HSDB - Hazardous Substance Data Bank

³ Lyman et al, 1982, Handbook of Chemical Property Estimation Methods

⁴ Verschueren, 1983, Handbook of Environmental Data on Organic Chemicals

⁵ US-EPA Region 9, PRGs, 1998 (Physical properties table)

⁶ CRC, 1971, Handbook of Chemistry and Physics

⁷ Cal-EPA OEHA, 04/1998 Draft, Public Health Goal for Methyl Tertiary Butyl Ether (MTBE) in drinking water

⁸ US-EPA Soil Screening Guidance: User Guide, 1996

⁹ PTS Laboratories, Inc. 1998, Personal communication

TABLE 6-2 (b)
SUMMARY OF CHEMICAL PROPERTIES
(MIXTURES)

Mixture	Molecular weight mg/mole ¹ (MW)	Relative Viscosity (PSH to water) ² (μ_{ro})	Specific Gravity (gm/cm ³) ² (ρ_o)	Relative Specific Gravity (dimensionless) ² (γ_{ro})
Gasoline	100,000	0.5	0.73	0.73
Kerosene	200,000	2.0	0.79	0.79
Diesel	200,000	7.0	0.83	0.83
Fuel Oil	200,000	25.0	0.90	0.90
Waste Oil	400,000	60.0	0.92	0.92

Note: The molecular weights for the fuel mixtures presented are assumed values based on average carbon chain length. If accurate values are available those values should be used.

¹ Larry Kunkel, PTL Laboratories, 1998 Personal Communication

² Gary Beckett, Aqui-Ver, 1998 Personal Communication

TABLE 6-3
REPRESENTATIVE RANGE OF VALUES FOR SOIL PHYSICAL PROPERTIES

Soil Type	Total Porosity θ (%)	Dry Bulk Density ρ_b (gm/cm ³)	Water Content* (% by weight)	Water Content* θ_w (% by volume)	Air-filled Porosity* θ_a (% by volume)	Hydr. Cond. K (cm/sec)	TOC (fraction)
Gravel	25-44	1.50-2.00	1-2	2-3	23-41	10 ⁻¹ -10 ³	0.01
Sandy Gravel	25-46	1.45-2.00	1-2	2-3	23-43	10 ⁻² -10 ⁰	0.01
M-C Sand	25-51	1.30-2.00	2-5	4-7	21-44	10 ⁻³ -10 ⁰	0.01
Fine Sand	25-51	1.30-2.00	5-8	10-11	15-40	10 ⁻⁴ -10 ⁻²	0.01
Silty Sand	25-51	1.30-2.00	5-8	10-11	15-40	10 ⁻⁵ -10 ⁻³	0.01
Silt	36-51	1.30-1.70	18-20	26-31	5-25	10 ⁻⁶ -10 ⁻⁴	0.01
Clay	47-75	0.68-1.40	29-40	27-41	7-48	10 ⁻⁹ -10 ⁻⁶	0.01

* Based on the soil's specific retention

TABLE 6-4
CONSERVATIVE DEFAULT VALUES FOR VARIOUS PHYSICAL PROPERTIES

VARIABLE	DESCRIPTION	DEFAULT VALUE	SOURCE
D	depth of groundwater mixing zone	100 cm	DEH
E	indoor air exchange rate	0.50 exchanges/hour (resid) 0.83 exchanges/hour (com)	ASTM, 1995 ASTM, 1995
f_{oc}	weight fraction of organic carbon in soil	0.01 (TOC/1,000,000)	DEH
$MF_{(benzene/TPH)}$ Fresh gasoline	mole fraction of fresh gasoline	0.01 to 0.03 (dimensionless)	LUFT, 1988
q_c	critical flow rate	1×10^{-7} cm/sec	DEH
R	universal gas constant	8.2×10^{-5} atm-m ³ /mole-K	Lyman, 1989
Rh	room height	2.44 m	DEH
Sb	slab attenuation factor	1.0 no slab (dirt floor) 0.1 old slab 0.01 new/improved slab	DEH DEH DEH
T	temperature	293 °K (Stand. Temp. 20°C)	DEH
θ	total soil porosity	0.3 (dimensionless)	DEH
θ_a	air filled porosity	0.2 (dimensionless)	DEH
θ_w	water filled porosity	0.1 (dimensionless)	DEH
ρ_b	dry bulk density	1.85 gm/cm ³	DEH
ρ_w	density of water	1.00 gm/cm ³	Lyman, 1989

7. NAPL Migration in Soil

An extensive discussion on the investigation and behavior of non-aqueous phase liquids (NAPL, free product) is provided in [Section 5.VII](#). To evaluate the potential presence of NAPL in the soils at a site, the following three levels of evaluation can be used.

a. Level 1 Evaluation

The following procedure is recommended for a Level 1 evaluation to describe the NAPL immobility (residual saturation).

- (1) Identify the worst-case soil impacts at the site. This should include the highest permeability soil and the soil with the highest contaminant concentration. This may represent two separate soil types.
- (2) Determine the soil characteristics. Soils must be described by using ASTM-D2487 (Unified Soil Classification System). If site-specific soil analysis is not available, contact the agency Project Manager on the applicability of using the visual soil description outlined in ASTM-D2488.
- (3) Subsurface soils should be evaluated for the potential of “finger flow” movement of contaminants. It is recognized that “finger flow” is present to a degree in most cases. This condition is found frequently in cases where there are fine-grained soils overlaying uniform clean sands and/or coarse-grained sands. “Finger flow” may pose a significant problem, and installation of a groundwater monitoring well may be required to evaluate potential impacts to groundwater.
- (4) Select the petroleum product that was released at the site. If the petroleum product is a mixture, assume the lighter product as the product of concern. If the product is not listed in the [Table 5-3 in Section 5](#), then proceed to Level 2 evaluation.
- (5) Compare the residual saturation in [Table 5-3 in Section 5](#) to the highest TPH concentration from the site. If the site value is **less than** the table value for residual saturation, the contaminant is considered to be below residual saturation. This will indicate that the contaminant is not mobile as an NAPL. If the site value is **greater than** the table value, the contaminant or petroleum hydrocarbon is above the residual saturation and may be mobile.
- (6) Review subsequent guidance sections regarding evaluation of soil leachability and potential impacts to groundwater.

b. Level 2 Evaluation

The following procedure is recommended for a Level 2 evaluation. This procedure uses site-specific data in the analytical model provided. Commonly, the site-specific data used are the most sensitive variables in the analytical model. This can include the soil concentrations, soil properties, and NAPL characteristics.

- (1) Identify the worst-case soil impacts at the site. These should include the highest permeability soil and the soil with the highest contaminant concentration. Two separate soil types may be represented.

- (2) Determine the soil characteristics. All soils must be described by using ASTM-D2487. If the saturated hydraulic conductivity of the soil is unknown, select the appropriate soil type from the **Table 5-3 in Section 5**. Conductivity decreases logarithmically from gravel to clay. Laboratory measurement of hydraulic conductivity (or permeability) of the appropriate impacted soils can reduce uncertainty and justify a less conservative screening evaluation. The appropriate laboratory test for permeability or hydraulic conductivity is ASTM Method D2484 or D5084.
- (3) Subsurface soils should be evaluated for the potential of “finger flow” movement of contaminants. It is recognized that “finger flow” is present to a degree in most cases. This condition is found frequently in cases where there are fine-grained soils overlaying uniform clean sands and/or coarse-grained sands. “Finger flow” may pose a significant problem, and installation of a groundwater monitoring well may be required to evaluate potential impacts to groundwater.
- (4) Determine the petroleum characteristics by using **Tables 6-2 (a) and (b)**. If the petroleum product is a mixture, assume the lighter, more refined product as the product of concern.
- (5) Calculate the residual saturation for the site using Equations 5-3 and 5-4 in **Section 5.VII**.
- (6) Compare the calculated residual saturation to the highest TPH concentration from the site. If the site value is less than the calculated value (C_s), the contaminant is considered to be below residual saturation. This will indicate that the contaminant is not mobile as a NAPL. If the site value is greater than the calculated value (C_s), the contaminant or petroleum hydrocarbon is above the residual saturation and may be mobile.
- (7) Review subsequent guidance sections regarding evaluation of soil leachability and potential impacts to groundwater.

c. Level 3 Evaluation

Before proceeding with a Level 3 evaluation, it is important to discuss your approach with the agency Project Manager.

If the site does not pass the Level 1 or Level 2 evaluations as outlined above, a more detailed evaluation may be completed. This evaluation may include performing an NAPL mobility-screening test. Please refer to **Section 5.VII.C** for the recommended testing procedures.

8. Leaching and Migration in Soil

The next step in establishing site-specific soil cleanup goals to protect water quality is to determine how much of a contaminant will leach from the soil. The following equilibrium equations may be used to calculate a maximum concentration in the pore water of a soil.

When NAPL is present in the soil's pore space, Equations 6-1 and 6-2 should be used to calculate the maximum pore water concentration.

$$C_w = MF * S * \frac{1000 \text{ ug}}{1 \text{ mg}} \quad \text{Equation 6-1}$$

Where:

- C_w = the concentration in pore water (ug/l)
- MF = the mole fraction (dimensionless)
- S = the pure component aqueous solubility (mg/l-H₂O)

$$MF = \frac{C_s / MW}{C_{s(TPH)} / MW_{(TPH)}} \quad \text{Equation 6-2}$$

Where:

- MF = the mole fraction (dimensionless)
- C_s = the concentration of compound in soil (mg/kg)
- C_{sTPH} = the concentration of TPH in soil (mg/kg)
- MW = the molecular weight of the compound in soil (mg/mole)
- $MW_{(TPH)}$ = the molecular weight of TPH (mg/mole)

When immiscible hydrocarbons are not present in the pore space, Equation 6-3 should be used to calculate the maximum leachate concentration.

$$C_w = \frac{C_s * \rho_b}{\theta_w + K_d * \rho_b + H * \theta_a} * \frac{1 \text{ kg}}{1000 \text{ gm}} * \frac{1000 \text{ cm}^3}{1 \text{ l}} * \frac{1000 \text{ ug}}{1 \text{ mg}} \quad \text{Equation 6-3}$$

Where:

- C_w = the concentration in soil pore water (ug/l)
- C_s = the concentration of compound in soil (mg/kg)
- ρ_b = the dry bulk density of soil (gm/cm³)
- θ_w = the water filled porosity (dimensionless)
- θ_a = the air filled porosity (dimensionless)
- K_d = the soil/water distribution coefficient (cm³/gm)
= $K_{oc} * f_{oc}$
- K_{oc} = the organic carbon partitioning coefficient (cm³/gm)
- f_{oc} = the weight fraction of organic carbon in soil = TOC/10,000
- H = the Henrys Law Constant (dimensionless)

A more accurate method of determining the leachability of a contaminant in a soil is by using one of the following laboratory testing methods.

- **EPA Method 1312**, Synthetic Precipitation Leaching Procedure (SPLP), or
- **ASTM Method D4874-95**, Leaching Solid Material in a Column Apparatus.

Details on the use of these methods are presented in **Section 5.VIII** of this manual.

One or more of the following three levels of evaluation can be used to determine the solubility of a contaminant in soil. The results can then be used to evaluate the potential impact to groundwater.

a. Level 1 Evaluation

The Level 1 evaluation assumes that the calculated pore water concentration from Equations 6-1 and 6-2 directly impacts groundwater without dilution or biodegradation. Tables 6-5 and 6-6 provide the maximum mole fraction of the contaminant of concern that can be in soil to achieve the designated water quality goals established in beneficial use areas and non-beneficial use areas located near surface waters. These tables were generated with relatively conservative input parameters.

TABLE 6-5
GROUNDWATER WITH DESIGNATED BENEFICIAL USE
MAXIMUM SOIL CONTAMINATION BASED ON SOLUBILITY (NO
ATTENUATION)

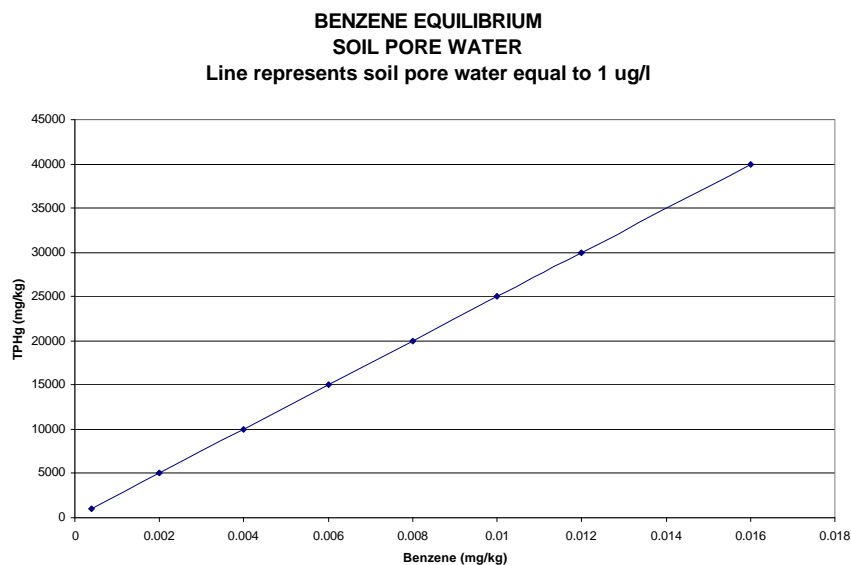
COMPOUND	Water Quality Goal (ug/l)	Solubility (ml/l - H ₂ O)	Mole Fraction (dimensionless)	TPH in Soil (mg/kg)	Concentration in Soil (mg/kg)
Benzene	1.0	1800	5.76×10^{-7}	1000	0.00045
Benzene	1.0	1800	5.76×10^{-7}	5000	0.00225
Benzene	1.0	1800	5.76×10^{-7}	10000	0.00450
Toluene	150	530	2.83×10^{-4}	1000	0.261
Toluene	150	530	2.83×10^{-4}	5000	1.30
Toluene	150	530	2.83×10^{-4}	10000	2.61
Ethylbenzene	700	170	4.12×10^{-3}	1000	4.36
Ethylbenzene	700	170	4.12×10^{-3}	5000	21.8
Ethylbenzene	700	170	4.12×10^{-3}	10000	43.6
Xylene	1,750	180	9.72×10^{-3}	1000	10.3
Xylene	1,750	180	9.72×10^{-3}	5000	51.6
Xylene	1,750	180	9.72×10^{-3}	10000	103
Naphthalene	20	31	6.46×10^{-4}	1000	0.414
Naphthalene	20	31	6.46×10^{-4}	5000	2.07
Naphthalene	20	31	6.46×10^{-4}	10000	4.14
Benzo(a)pyrene	0.2	0.00162	9.51×10^{-2}	1000	120
Benzo(a)pyrene	0.2	0.00162	9.51×10^{-2}	5000	600
Benzo(a)pyrene	0.2	0.00162	9.51×10^{-2}	10000	1,200
MTBE	13	48000	2.71×10^{-7}	1000	0.000239
MTBE	13	48000	2.71×10^{-7}	5000	0.00191
MTBE	13	48000	2.71×10^{-7}	10000	0.00239

Note: ug/l = micrograms per liter

TABLE 6-6
GROUNDWATER WITH NO DESIGNATED BENEFICIAL USE
(<1000 FT FROM A SURFACE WATER)
MAXIMUM SOIL CONTAMINATION BASED ON SOLUBILITY (NO
ATTENUATION)

COMPOUND	Water Quality Goal (ug/l)	Solubility (mg/l - H ₂ O)	Mole Fraction (dimensionless)	TPH in Soil (mg/kg)	Concentration in Soil (mg/kg)
Benzene	400	1800	2.22×10^{-4}	1000	0.173
Benzene	400	1800	2.22×10^{-4}	5000	0.867
Benzene	400	1800	2.22×10^{-4}	10000	1.73
Toluene	5,000	530	9.43×10^{-3}	1000	8.69
Toluene	5,000	530	9.43×10^{-3}	5000	43.4
Toluene	5,000	530	9.43×10^{-3}	10000	86.9
Ethylbenzene	430	170	2.53×10^{-3}	1000	2.68
Ethylbenzene	430	170	2.53×10^{-3}	5000	13.4
Ethylbenzene	430	170	2.53×10^{-3}	10000	26.8
Xylene	10,000	180	5.56×10^{-2}	1000	58.9
Xylene	10,000	180	5.56×10^{-2}	5000	294
Xylene	10,000	180	5.56×10^{-2}	10000	589
Naphthalene	2,350	31	7.58×10^{-2}	1000	48.6
Naphthalene	2,350	31	7.58×10^{-2}	5000	243
Naphthalene	2,350	31	7.58×10^{-2}	10000	486
Benzo(a)pyrene	4.4	0.00162	2.73×10^{-0}	1000	3,450
Benzo(a)pyrene	4.4	0.00162	2.73×10^{-0}	5000	17,250
Benzo(a)pyrene	4.4	0.00162	2.73×10^{-0}	10000	34,500

The data presented in these tables can be graphed with the compound of concern on the x-axis and TPH on the y-axis. The graph presented below shows benzene and a water quality goal of 1 ug/l.



When the site-specific TPH and benzene concentrations plot below the 1 ug/l line on the graph, the residual soil contamination will not generate a leachate (pore water) that exceeds the water quality goal.

- (1) Identify worse case soil impacts at the site. This should include the highest permeability soil and the soil with the highest contaminant concentration. This may represent two separate soil types.
- (2) Determine the soil characteristics. All soils must be described by using ASTM-D2487. If site-specific soil analysis is not available, contact the agency Project Manager on the applicability of using the visual soil description outlined in ASTM-D2488.
- (3) Exercise caution if a site is underlain predominantly by clay or silts.
- (4) Determine the existing and potential beneficial uses of groundwater in addition to the actual and probable future uses in the proximity of the subject site.
- (5) Compare the concentrations of the compounds detected at the site to the concentrations listed in Tables 6-5 and 6-6.
- (6) If the site-specific soil concentrations are greater than the values in Tables 6-6 or 6-7, proceed to a Level 2 evaluation. If the subsurface soils or rock conditions are fractured, no attenuation should be considered and groundwater impacts need to be investigated and monitored. If the concentrations at the site are less than the values in Table 6-5 or 6-6, residual contamination levels pose no threat to groundwater.

b. Level 2 Evaluation

The Level 2 evaluation not only calculates pore water concentration of the contaminant in the soil; it also incorporates the transport processes of the pore water through the vadose zone to groundwater. The environmental fate of a contaminant through the vadose zone is controlled by a number of factors. These factors include volatilization, retardation, sorption, biodegradation, and dilution.

The following evaluation method takes into account the factors of biodegradation and dilution. Volatilization was not included in this analysis due to the required level of understanding needed to evaluate multiphase relationships at a site. Retardation and sorption were not included since these processes generally slow the contamination front rather than reduce the level of contamination.

- (1) Under most field conditions, the effective unsaturated hydraulic conductivity is controlling the infiltration rate. Darcy's Law for vertical flow (Equation 6-4) defines this. The darcy velocity (q_z) is the average velocity of water over a cross-sectional area of porous material.

$$q_z = K_{avg} \frac{\Psi + Z}{Z} \quad \text{Equation 6-4}$$

Where:

q_z	=	darcy velocity (cm/sec)
K_{avg}	=	average vertical unsaturated hydraulic conductivity (cm/sec)
Ψ	=	capillary suction component (cm)
Z	=	gravitation component (cm)

At later infiltration times the capillary suction component of the gradient will drop out and the gradient is reduced to a value of one. Equation 6-4 then can be rewritten as follows:

$$q_z = K_{avg} \quad \text{Equation 6-5}$$

Where:

q_z	=	darcy velocity (cm/sec)
K_{avg}	=	average vertical unsaturated hydraulic conductivity (cm/sec)

To determine the effective unsaturated hydraulic conductivity for a soil, detailed laboratory testing needs to be completed. The effective vertical unsaturated hydraulic conductivity in reality is a value somewhere between the hydraulic conductivity at the wetting front (at low moisture content) and the hydraulic conductivity in the transmission zone (at or near saturation). It is conservative to assume the effective vertical unsaturated hydraulic conductivity is 50% of the saturated laboratory hydraulic conductivity. In most cases this assumption will result in an over estimation of the effective vertical unsaturated hydraulic conductivity. This assumption is not conservative in cases in which there are coarse sands and gravels.

- (2) Determine the percolation velocity (v).

The darcy velocity (q_z) calculated in Equation 6-5 is then divided by the change in volumetric moisture in the unsaturated zone to give the infiltration velocity. Generally the effective change in volumetric moisture is unknown and depends on the capillary characteristics of the soil. A conservative estimate may be made by using the calculated darcy velocity (q_z) and dividing it by the soils-specific yield.

$$\theta = S_r + S_y \quad \text{Equation 6-6}$$

Where:

θ	=	the total porosity (dimensionless)
S_r	=	the specific retention (dimensionless)
S_y	=	the specific yield (dimensionless)

To obtain the infiltration velocity, use Equation 6-7.

$$v = \frac{q_z}{S_y} \quad \text{Equation 6-7}$$

Where: v = the infiltration velocity (cm/sec)
 q_z = the darcy velocity (cm/sec)
 S_y = the specific yield (dimensionless)

- (3) Determine the time to reach groundwater (T_c).

The following equation is used to calculate the number of seconds it will take the contaminant to reach groundwater.

$$T_c = \frac{L}{v} \quad \text{Equation 6-8}$$

Where: T_c = the time to reach groundwater (sec)
 L = the distance of travel (cm)
 v = the infiltration velocity (cm/sec)

The distance of travel (L) is the minimum vertical distance between soil contamination and groundwater.

- (4) Determine the pore water concentration at the water table interface prior to dilution (C_f).

Biodegradation is known to reduce the level of contamination. In an aerobic environment, biodegradation of fuels generally follows a first order decay relationship. The biodegradation rates ($t_{1/2}$) are not provided. Caution should be exercised when using first order decay rates ($t_{1/2}$) at high concentrations. Work by Bekins et al, 1998, suggests that the degradation rates for benzene tend to over-estimate biodegradation when leachate concentration (benzene) is greater than 1,000 ug/l. This is also true when the combination of benzene, toluene, ethylbenzene and xylene (BTEX) is greater than 5,000 mg/l.

The biodegradation rates ($t_{1/2}$) used in the following equation will have to be either obtained from the literature or from site data. At the request of the agency, copies of references used may be required.

The following equation is used to calculate the pore water concentration at the water table.

$$\log (C_f) = \log [C_w] - [(T_c / 2.3) * (0.693 / t_{1/2})] \quad \text{Equation 6-9}$$

Where: C_f = the final concentration in soil pore water at water table (ug/l)
 C_w = the concentration in soil pore water (ug/l)
 T_c = the time to reach groundwater (sec)
 $t_{1/2}$ = the biodegradation half life of contaminant (sec)

- (5) Determine the calculated impact to groundwater (C_{gw}).

The potential dilution of pore water in groundwater depends on the proportionality of the mass of input (pore water) and the background mass flux of the groundwater system. A simple dilution factor can be calculated as the ratio of the vertical recharge divided by the total discharge in the mixing zone.

To calculate the unit mass flux in the groundwater system, the vertical mixing zone is assumed to be approximately 3 feet (100 centimeters) in depth. This unit mass flux is calculated by using the following equation.

$$Q_{gw} = K * i * d * 1 \text{ cm} \quad \text{Equation 6-10}$$

Where:

- Q_{gw} = unit mass flux of groundwater (cm^3/sec)
- K = saturated hydraulic conductivity (cm/sec)
- i = gradient (dimensionless)
- d = depth of groundwater mixing zone (cm)

The following equation is used to calculate the effective dilution factor in the groundwater-mixing zone.

$$D_f = \frac{v * A_v}{(v * A_v) + Q_{gw}} \quad \text{Equation 6-11}$$

Where:

- D_f = the dilution factor (dimensionless)
- v = the infiltration velocity (cm/sec)
- A_v = the area of infiltration (cm^2)
- Q_{gw} = unit mass flux of groundwater (cm^3/sec)

The final calculations apply the dilution factor (D_f) to the pore water concentration (C_f) to calculate the concentration in groundwater (C_{gw}).

$$C_{gw} = C_f * D_f \quad \text{Equation 6-12}$$

Where:

- C_{gw} = the calculated concentration in groundwater (ug/l)
- C_f = the final concentration in soil pore water at water table (ug/l)
- D_f = the dilution factor (dimensionless)

- (6) Compare the calculated impact to the water quality objectives as specified by the RWQCB Basin Plan. If concentrations are greater than the water quality objectives, soil remediation should be considered or a Level 3 evaluation should be undertaken. Alternatively, the calculated concentrations may be used as input parameters into a groundwater flow model to evaluate the potential impacts to a receptor.

c. Level 3 Evaluation*

* Discussion with DEH Project Manager prior to proceeding with a Level 3 evaluation is required.

This level of evaluation includes the use of more complex computer models that describe the environmental fate and transport of a contaminant in the subsurface. These models may be capable of modeling complex subsurface conditions such as multi-layered geologic conditions, anaerobic conditions, and fractured geologic environments. The computer model used should be available in the public domain, peer reviewed, and validated. DEH and the RWQCB may request copies of the model and model documentation.

If there is an impact to groundwater above established action levels, further investigation and/or remediation will need to be completed.

9. Vapor-Phase Migration

This section provides a narrative of the vapor diffusion process and the different methods used to calculate soil gas concentrations. In this discussion and the example calculations provided in [Appendix F.II](#), benzene is used as the constituent of concern. This methodology may be used to estimate the potential exposure to any volatile compound of concern.

The calculations presented in this section represent a method to estimate vapor diffusion of benzene from subsurface gasoline-contaminated media to indoor air space. Benzene is considered the most toxic carcinogenic compound in gasoline and will serve as the indicator compound for this example. The exposure pathway of concern is the upward diffusion of benzene through soil gas and into indoor air. Buildings with basements or other subterranean structures may require more complex analyses that consider advective or pressure-driven flow.

A simplified environmental fate and transport analysis is used to evaluate the inhalation exposure pathway for benzene as shown in Figure 6-2. This process is divided into five components. The analysis considers diffusive flux, assuming a non-diminishing steady state source of benzene in the subsurface. Additionally, it assumes that the system is in dynamic equilibrium.

Default values used by DEH are presented in Tables 6-2 through 6-4. Should site-specific soil physical properties be used as input parameters, it is recommended that two representative soil samples be collected from each lithologic soil unit at the site. The site-specific soil physical properties should include:

- Bulk density
- Total porosity, water-filled porosity, air-filled porosity
- Soil moisture content
- Total organic carbon
- Grain size distribution and/or clay content

Samples should be taken in the unsaturated zone and not in the capillary fringe so that they are representative of the zone where diffusion is occurring. Representative soil samples can be collected in three 3-inch to 6-inch rings. Collected samples should be relatively undisturbed where possible. Samples collected for soil moisture content are measured in a laboratory by using ASTM Method D2216-92. Samples for total organic carbon should be collected and analyzed in accordance with the Walkley Black method for soils (ASTM, 1995).

a. Calculation of Soil Gas Concentrations

The concentration of benzene in soil gas is calculated by one of the following methods, using samples collected from the area or zone where the source of contamination is located.

(1) Groundwater with NAPL

For sites where NAPL is present, the soil gas concentration in the area of the source is calculated by using the Ideal Gas Law and Raoult's Law as presented in Equation 6-13. The **mole fraction (MF)** of benzene in the NAPL is used. The mole fraction of benzene in fresh gasoline ranges from 0.01 to 0.03 (dimensionless). If the NAPL has been analyzed, the mole fraction of benzene can be calculated by dividing the benzene concentration by the TPH concentration multiplied by the ratio of the molecular weight of benzene to the average molecular weight of the mixture of gasoline. To calculate the mole fraction from available laboratory data, use Equation 6-2.

(2) Soil with TPH Concentrations > 100 mg/kg

For sites where the TPH concentrations in soil exceed 100 mg/kg, the benzene concentration in soil gas is calculated by using the Ideal Gas Law and Raoult's Law for NAPL conditions as shown in Equation 6-13. To calculate the mole fraction from available laboratory data, use Equation 6-2.

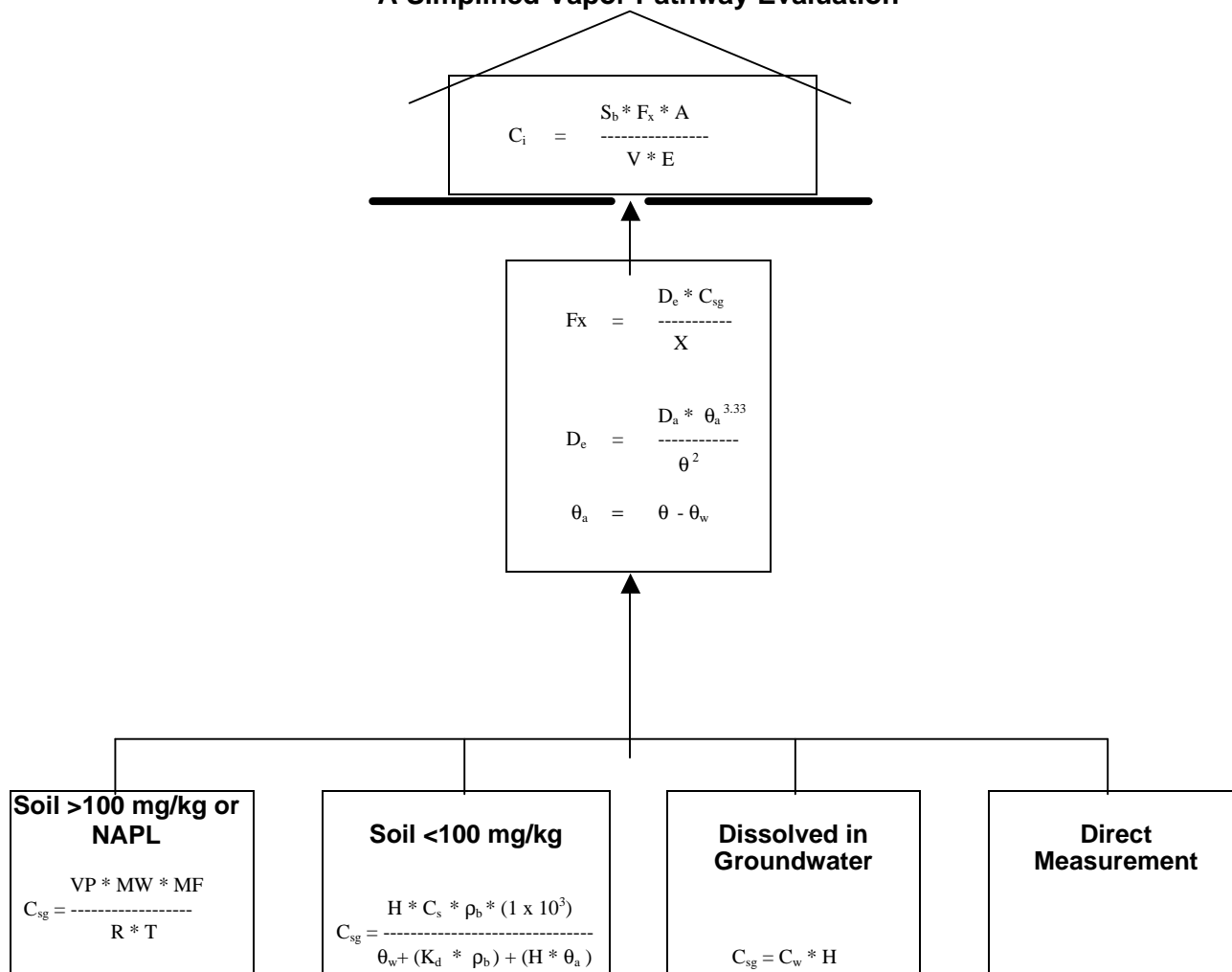
(3) Soil with TPH Concentrations < 100 mg/kg

For sites where the TPH concentrations in soil are less than 100 mg/kg, the benzene concentration in soil gas is calculated based on the equilibrium partitioning between the soil, the moisture, and vapor phase by using the fugacity equation (Equation 6-14).

(4) Groundwater with Dissolved Contamination (No NAPL)

For sites where benzene is dissolved into either groundwater or soil pore water, the benzene concentration in soil gas is calculated by using the Henry's Law Constant as presented in Equation 6-15.

FIGURE 6-2
A Simplified Vapor Pathway Evaluation



A	=	the room floor area (m ²)
C _s	=	the contaminant concentration in the soil (mg/kg)
C _{sg}	=	the contaminant concentration in the soil vapor (mg/m ³)
C _w	=	the concentration in pore water (ug/l)
C _i	=	the indoor air concentration (mg/m ³)
D _a	=	the diffusion coefficient of compound in air (cm ² /sec)
D _e	=	the effective air diffusion coefficient (cm ² /sec)
E	=	the indoor air exchange rate per hour (hr ⁻¹)
F _x	=	the contaminant vapor flux (mg/hr-m ²)
H	=	the Henry's law constant (dimensionless)
K _d	=	the soil/water distribution coefficient (cm ³ /gm)
MF	=	the mole fraction (dimensionless)
MW	=	the molecular weight of the compound of concern (mg/mole)
R	=	the universal gas constant (atm-m ³ /mole-K)
T	=	the temperature in degrees Kelvin (°K)
S _b	=	the slab attenuation factor (dimensionless)
V	=	the room volume (m ³)
VP	=	the contaminant vapor pressure at STP (atm)
X	=	the depth or distance to contamination in the vadose zone (m)
θ	=	the total soil porosity (dimensionless)
θ _a	=	the air filled porosity (dimensionless)
θ _w	=	the water filled porosity (dimensionless)
ρ _b	=	the dry bulk density of soil (gm/cm ³)

(5) Direct Measurement of Soil Gas

Experience has shown the benzene concentration in soil gas can be overestimated by using the methods described above. These methods do not account for biodegradation and natural attenuation. These processes may account for the difference between the calculated soil gas and the direct measurement of soil gas. Direct measurements of soil gas can be used only if the system can be adequately characterized both spatially and temporally, and the samples collected are representative of exposure scenarios for the receptor. Furthermore, detection limits for soil gas survey must be sufficiently low to be used for risk analysis. Please refer to [Section 5.IV](#) for procedures on soil gas sampling.

b. Calculation of Flux

The simplified equation used in this section (Equation 6-16) describes soil gas flux from the source area to the base of a structure. The equation assumes diffusion as the driving force for mass transport. The equation is highly dependent on soil moisture. Soil moisture content values should preferably be measured in representative soil samples collected from the site.

c. Calculation of Indoor Air Concentration

The indoor air contaminant concentration is dependent on the "effective area" through which the flux occurs and the indoor air exchange rate with outdoor air. For residential buildings, the "effective area" must include the entire floor area of the building. For commercial and industrial buildings the "effective area" may be less than the entire floor area. Any reduction in the "effective area" must be justified. The indoor air exchange rate with outdoor air may be taken to be 0.5 exchange per hour for residential construction. Rates for commercial buildings may be obtained from the architect or engineer, or the default value of 0.83 exchange per hour should be used.

d. Equations Used to Model Migration of Vapors from Subsurface Contamination

This section presents the equations used to calculate soil gas, effective diffusion coefficients, diffusive mass flux, and indoor air concentration.

(1) Calculation of Soil Gas Concentrations

Soil gas concentrations can be determined based on one of the following methods. With the exception of direct measurement, the method used is a function of site conditions.

- For Groundwater with NAPL

It is assumed that the vapor immediately above the groundwater is in equilibrium with the NAPL present. The vapor concentration is a function of the contaminant's mole fraction and vapor pressure:

$$C_{sg} = \frac{VP * MW * MF}{R * T} \quad \text{Equation 6-13}$$

Where:

- C_{sg} = the contaminant concentration in the soil vapor (mg/m³)
- VP = the contaminant vapor pressure at STP (atm)
- MW = the molecular weight of the compound of concern (mg/mole)
- MF = the mole fraction (dimensionless)
- R = the universal gas constant (atm-m³/mole-K)
- T = the temperature in degrees Kelvin (Standard temperature of 293°K)

- From Soil with TPH Concentrations > 100 mg/kg

At these concentrations, it is assumed that NAPL and C_{sg} depend upon the contaminant's mole fraction and vapor pressure:

Use Equation 6-13.

- From Soil with TPH Concentrations < 100 mg/kg

In this case, C_{sg} is computed based upon the equilibrium partitioning between the soil, moisture, and vapor phases. If benzene data are not available, the benzene concentration in soil can be estimated by using the TPH concentration and the mole fraction of benzene in gasoline (0.01 to 0.03).

Equation 6-14

$$C_{sg} = \frac{H * C_s * \rho_b}{\theta_w + (K_d * \rho_b) + (H * \theta_a)} * (1 \times 10^{-3} \text{ kg/gm}) * (1 \times 10^6 \text{ cm}^3/\text{m}^3)$$

Where:

- C_{sg} = the contaminant concentration in the soil vapor (mg/m³)
- H = the Henrys Law constant (dimensionless)
- C_s = the concentration of compound in soil (mg/kg)
- ρ_b = the dry bulk density of soil (gm/cm³)
- K_d = the soil/water distribution coefficient (cm³/gm)
= $K_{oc} * f_{oc}$
- K_{oc} = the organic carbon partitioning coefficient (cm³/gm)
- f_{oc} = the weight fraction of organic carbon in soil (dimensionless)
= $TOC/10,000$
- θ_a = the air filled porosity (dimensionless)
- θ_w = the water filled porosity (dimensionless)

- From Groundwater with no NAPL (No Liquid Phase Hydrocarbons)

It is assumed the vapor concentration immediately above the groundwater is in equilibrium with the groundwater. The concentration in soil gas is given by the water concentration times the dimensionless Henry's Law Constant:

$$C_{sg} = C_w * H \quad \text{Equation 6-15}$$

Where: C_{sg} = the contaminant concentration in the soil vapor (mg/m³)
 C_w = the concentration of compound in groundwater (ug/l)
 H = the Henry's Law Constant (dimensionless)

- Direct Measurement of Soil Gas

Data provided from soil gas surveys are typically reported in micrograms per liter-vapor (ug/l-vapor) or parts per million by volume (ppmV). These values should be converted to the proper units required for the flux equation (mg/m³). Standard conversions are provided in the following [Table 6-7](#).

(2) Calculation of Flux

The flux of a contaminant is calculated from Fick's First Law as:

$$F_x = \frac{D_e * C_{sg}}{X} * \frac{3,600 \text{ sec/hr}}{10,000 \text{ cm}^2/\text{m}^2} \quad \text{Equation 6-16}$$

Where: F_x = the contaminant vapor flux (mg/hr-m²)
 D_e = the effective air diffusion coefficient (cm²/sec)
 C_{sg} = the contaminant concentration in the soil vapor (mg/m³)
 X = the depth or distance to contamination in the vadose zone (m)

The diffusion process is considered to be molecular diffusion. Buildings with basements or subterranean structures may create pressure gradients that induce advective transport, which requires a different analysis than presented here. The value for the diffusion coefficient is taken as the molecular diffusivity for the contaminant corrected for the effects of the soil column as:

$$D_e = \frac{D_a * \theta_a^{3.33}}{\theta^2} \quad \text{Equation 6-17}$$

Where: D_e = the effective air diffusion coefficient (cm²/sec)
 D_a = the diffusion coefficient of compound in air (cm²/sec)
 θ_a = the air filled porosity (dimensionless)
 θ = the total soil porosity (dimensionless)

**TABLE 6-7
GAS CONCENTRATION UNITS – CONVERSION**

UNITS	TO CONVERT TO:	MULTIPLY BY:
ug/l	mg/m ³	1
ug/m ³	mg/m ³	0.001
ppmv	mg/m ³	MW/24 (20°C)
ppbv	mg/m ³	MW/24,000 (20°C)
ug/l	ug/m ³	1000
ug/l	ppbv	24,000/MW (20°C)
ug/l	ppmv	24/MW (20°C)
ppbv	ppm	0.001
ppmv	ppbv	1000

Notes: ug/l = micrograms per liter
 mg/m³ = milligrams per cubic meter
 ug/m³ = micrograms per cubic meter
 ppmv = parts per million by volume
 ppbv = part per billion by volume
 MW = molecular weight of compound (g/mole). Values presented in
 Table 6-2(a) must be converted from mg/kg to g/mole

(3) Calculation of Indoor Air Concentration

The indoor air concentration is dependent upon the area through which the flux passes and the indoor air exchange rate with outdoor air. The flux is considered attenuated by the presence of a concrete slab. The default slab attenuation factors are provided in **Table 6-4**. For residential buildings, an indoor air exchange rate of one building volume every 2 hours (or 0.5 exchange per hour) is typically used. Commercial buildings typically have higher exchange rates, which can be obtained from the building architect or engineer. If site-specific air exchange rates are not available, the 0.83 exchange per hour rate should be used.

$$C_i = \frac{S_b * F_x * A}{V * E} = \frac{S_b * F_x}{R_h * E} \quad \text{Equation 6-18}$$

Where:

C_i	=	the indoor air concentration (mg/m ³)
S_b	=	the slab attenuation factor (dimensionless)
F_x	=	the contaminant vapor flux (mg/hr-m ²)
A	=	the room floor area (m ²)
V	=	the room volume (m ³)
E	=	the indoor air exchange rate per hour (hr ⁻¹)
R_h	=	the room height (m)

10. Groundwater Contaminant Transport

A wide variety of analytical and numerical groundwater transport models can be used to evaluate contaminant transport. DEH recommends use of a peer-reviewed model that has been demonstrated in the literature to be conservative, accurate, and appropriate to the site conditions.

11. Fate and Transport Model Proposal

An appropriately detailed written proposal describing the model selection process and rationale must be submitted to the regulatory agencies for review. The proposal should discuss the following:

- Purpose and scope of the fate and transport modeling analysis
- A statement of qualifications
- Summary of site assessment data
- Conceptual model
- Model selection criteria
 - List the objectives of the fate and transport analysis.
 - Describe the concepts and calculations utilized by the models.
 - Summarize strengths, weaknesses, assumptions, and uncertainties of models.
- Data requirements for fate and transport modeling

Discuss the site-specific input parameters to be used in the model. Include a discussion on data availability and quality, and describe any biases in the data that may be attributed to methods of collection or analysis. Discuss, justify, and document the sources of all assumed

values used for model input parameters. Correct the values that vary with temperature and pressure to the conditions found at the site being modeled.

Reasonable extrapolations of site-specific data are preferred to generic data from published literature sources. Commonly, fate and transport modeling is performed on one or more indicator compounds. Indicator compounds are typically chosen on the basis of mobility and toxicity.

Describe the methods (analytical, physical, experimental, etc.) that may be used to validate the results of the fate and transport model. If the model has been validated under similar conditions at another site, provide references and briefly outline the results. Discuss the applicability of the validation techniques used at another site to the site of concern.

Please note: In DEH's experience, the largest source of error in computer modeling is from using input parameters that are not in the correct units.

12. Fate and Transport Report

The fate and transport report must be complete and will be reviewed as a stand-alone document. The report may be included in the health risk assessment report. Data obtained from site assessment reports should be clearly presented. A single clear and concise interpretation of the data should be presented (include maps, plot plans, and cross-sections that clearly illustrate site conditions and contaminant distribution). The report must provide the model's predictions of future contaminant migration and distribution of contaminants in relation to receptors (include maps, plot plans and cross-sections). Include copies of model calibration runs and sensitivity analyses in an appendix.

Provide a detailed discussion of the results of the modeling analysis, which addresses the following items:

- Technical problems encountered and any new information concerning site conditions which resulted from the modeling analysis;
- Model input parameters which should be within the range of measured or expected site-specific values;
- Methods used to validate the model at the site;
- Conclusions of fate and transport modeling (include a synopsis of the important results with reference to the limitations and assumptions of the model used); and
- Discussion of the case status, additional work required, and recommendations for the future course of action at the site.

Since fate and transport modeling involves the interpretation of subsurface processes affecting contaminant migration, contaminant transformation and interpretations of geologic and hydrogeologic conditions, the fate and transport proposal needs to be reviewed and signed by a registered professional in the field of geology (a Registered Geologist [RG]).

C. Water Resource Impacts

In those areas designated in the RWQCB Basin Plan as having existing or potential beneficial uses for groundwater and surface waters, the water quality objectives are generally the MCLs for the compounds identified. In these areas the RWQCB considers the groundwater or surface water as a receptor.

II. Risk Characterization

Risk characterization is the process of evaluating the level of human health or ecological risk at a site. This is accomplished by integrating the results of the exposure and toxicity assessments.

The complexity and expense of the risk assessment will vary considerably depending on the site conditions, the type and extent of contamination, and the proposed site use. In an effort to conserve resources, a risk assessment can be done in a phased approach. Available site data, simple calculations, and conservative assumptions can be used initially. If the risk is acceptable under these "worst case" conditions, there may be no need to continue the risk assessment. If the risk is not acceptable, additional site-specific data and/or more complex models using more realistic assumptions should be used to further characterize the risk.

In order to provide a more realistic characterization of risk, some projects may require collection of additional site-specific data. When the collection of site-specific data is too difficult or costly, contaminant removal or treatment may be the best alternative.

DEH recommends that risk assessments adhere to the format presented in the U.S. EPA's document entitled "Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual, Part A, Interim Final (RAG), December 1989, EPA/540/1-89/002."

In summary, the calculation of risk is based on the summation of the calculated risk from each route of exposure. The routes of exposure to be considered are:

- Dermal
- Ingestion
- Inhalation

In most cases there are three exposure pathways that are relevant. These pathways are (1) inhalation from NAPL, (2) inhalation from residual soil contamination and groundwater contamination, and (3) ingestion of groundwater. These pathways are described in [Section 6.III.B.2](#). Other pathways have not been described herein. If other pathways exist at the site, they need to be included in the analysis to evaluate exposure.

The results of the analytical calculation from the exposure assessment and the corresponding chemicals' cancer SFs and RfDs from the toxicity assessment are then used in the following exposure calculation to calculate the health risk.

It is important to understand that health risk calculations only estimate the incremental increase in risk resulting from residual contamination. Except for lead, risks from ambient sources are not estimated or considered in the methods presented.

The risk assessment report must contain objective and technically defensible conclusions. The report must include a discussion of the strengths and weaknesses by describing uncertainties, making statements of assumptions and limitations, and providing the scientific basis and rationale for each assumption. Model validation must also be discussed as applicable. Conclusions regarding the potential risk to human health and/or the environment must be based on current federal, state, and local guidelines. Risk assessment reporting format is described beginning in [Section 6.III.E](#).

1. List of exposure variables used in calculation of risk.

The following are provided for quick reference for Equations 6-19 through 6-27. Typical default values are presented in Table 6-8.

ABS	=	the absorption factor (dimensionless)
AD	=	the absorbed dose (mg/kg-day)
AF	=	the soil to skin adherence factor (mg/cm ²)
AT	=	the averaging time (days)
BW	=	the body weight (kg)
C _{gw}	=	the chemical concentration in groundwater (ug/l)
C _s	=	the chemical concentration in soil (mg/kg)
C _i	=	the indoor air concentration (mg/m ³)
PC	=	the chemical-specific dermal permeability constant (cm/hr)
ET	=	the exposure time (hr/24hr)
EF	=	the exposure frequency (days/yr)
EF _s	=	the exposure frequency (events/yr)
ED	=	the exposure duration (yr)
FI	=	the fraction of soil ingested from the contaminated source (dimensionless)
HI	=	the hazard index
HQ	=	the hazard quotient
IR	=	the inhalation rate (m ³ /day)
IR _w	=	the ingestion rate (l/day-water)
IR _s	=	the ingestion rate (mg/day-soil)
IT	=	the chemical intake (mg/kg-day)
RfD	=	the reference dose (mg/kg-day)
Risk	=	the estimate of health risk (excess cancer risk)
SA _w	=	the skin surface area available for contact (cm ²)
SA _s	=	the skin surface area available for contact (cm ² /event)
SF	=	the contaminant carcinogenic slope factor ([mg/kg-day] ⁻¹)

Either a Certified Industrial Hygienist (CIH) or a Diplomate American Board of Toxicology (DABT) should evaluate use of values other than those presented in Table 6-8.

2. The following are the human health exposure calculations from U.S. EPA's document entitled "Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual, Part A, Interim Final (RAGS), December 1989, EPA/540/1-89/002" for the three main exposure routes:

The following equations are used to calculate the risk to a receptor or individual from a specific exposure route. The intake or absorbed dose accounts for the specific route of exposure. Note that when the chemical of concern is a known carcinogen, the averaging time

(AT) is the number of days over a 70-year lifetime (25,500 days). Please note that for residential exposures, risk must include children and adult exposures.

a. Dermal

Dermal exposure can include exposure to either soil and/or water. The following equations are for dermal contact with a chemical of concern.

(1) Dermal contact with chemicals in water

Equation 6-19

$$AD = \frac{C_{gw} * SA_w * PC * ET * EF * ED * (1 \times 10^{-3} \text{ l/cm}^3) * (1 \times 10^{-3} \text{ mg/ug})}{BW * AT}$$

Where:

AD	=	the absorbed dose (mg/kg-day)
C_{gw}	=	the chemical concentration in groundwater (ug/l)
SA_w	=	the skin surface area available for contact (cm^2)
PC	=	the chemical-specific dermal permeability constant (cm/hr)
ET	=	the exposure time (hr/24hr-day)
EF	=	the exposure frequency (days/yr)
ED	=	the exposure duration (yr)
BW	=	the body weight (kg)
AT	=	the averaging time (days)

(2) Dermal contact with chemicals in soil

Equation 6-20

$$AD = \frac{C_s * SA_s * AF * ABS * EF_s * ED * (1 \times 10^{-6} \text{ kg/mg})}{BW * AT}$$

Where:

AD	=	the absorbed dose (mg/kg-day)
C_s	=	the chemical concentration in soil (mg/kg)
SA_s	=	the skin surface area available for contact (cm^2/event)
AF	=	the soil to skin adherence factor (mg/cm^2)
ABS	=	the absorption factor (dimensionless)
EF_s	=	the exposure frequency (events/yr)
ED	=	the exposure duration (yr)
BW	=	the body weight (kg)
AT	=	the averaging time (days)

TABLE 6-8
CONSERVATIVE DEFAULT VALUES FOR HEALTH RISK EXPOSURE

VAR.	DESCRIPTION	DEFAULT VALUE	SOURCE
ABS	Absorption factor	Chemical-specific (literature)	EPA, 1989
AF	Soil to skin adherence factor	1.0 mg/m ³	DEH
AT	Averaging time	25500 days (carcinogen) ED (non-carcinogen)	EPA, 1989
BW	Body weight	15 kg (child) 70 kg (adult)	EPA, 1991 EPA, 1989
ED	Exposure duration	25 years (commercial, adult only) 30 years (residential, adult only) 6 years / 19 years (commercial, child/ad.) 6 years / 24 years (residential, child/adult)	EPA, 1989 EPA, 1989 EPA, 1991 EPA, 1991
EF	Exposure frequency	250 days/year (commercial) 365 days/year (residential)	EPA, 1989 EPA, 1989
EF _s	Exposure frequency	Pathway specific	EPA, 1989
ET	Exposure time	0.5 days (commercial) - 12 hours/day 1.0 days (residential) – 24 hours/day	EPA, 1989 EPA, 1989
FI	Fraction of soil ingested	1 (100% for commercial & residential)	DEH
IR	Inhalation rate	10 m ³ /day (child) 20 m ³ /day (adult)	EPA, 1997 EPA, 1991
IR _s	Ingestion rate (soil)	100 mg/day (child) 200 mg/day (adult)	EPA, 1991 EPA, 1991
IR _w	Ingestion rate (water)	1 l/day (child) 2 l/day (adult)	EPA, 1989 DTSC,1994
PC	Dermal perm. Constant	Chemical-specific (literature)	EPA, 1989
SA _s	Skin surface area for contact (soil)	2,000 cm ² /day (child) 5,800 cm ² /day (adult)	DEH DEH
SA _w	Skin surface area for contact (water)	23,000 cm ² /day (adult/adult)	DEH

b. Ingestion

Chemicals in soil and/or water can be ingested. The following equations are to be used for ingestion.

(1) Ingestion of chemicals in drinking water

$$IT = \frac{C_{gw} * IR_w * EF * ED * (1 \times 10^{-3} \text{ mg/ug})}{BW * AT} \quad \text{Equation 6-21}$$

Where:

IT	=	the chemical intake (mg/kg-day)
C_{gw}	=	the chemical concentration in groundwater (ug/l)
IR_w	=	the ingestion rate (l/day-water)
EF	=	the exposure frequency (days/yr)
ED	=	the exposure duration (yr)
BW	=	the body weight (kg)
AT	=	the averaging time (days)

(2) Ingestion of chemicals in soil

$$IT = \frac{C_s * IR_s * FI * EF * ED * (1 \times 10^{-6} \text{ kg/mg})}{BW * AT} \quad \text{Equation 6-22}$$

Where:

IT	=	the chemical intake (mg/kg-day)
C_s	=	the chemical concentration in soil (mg/kg)
IR_s	=	the ingestion rate (mg/day-soil)
FI	=	the fraction of soil ingested from the contaminated source (dimensionless)
EF	=	the exposure frequency (days/yr)
ED	=	the exposure duration (yr)
BW	=	the body weight (kg)
AT	=	the averaging time (days)

c. Inhalation

Inhalation of chemical vapors inside a structure can be evaluated by using the following equation.

$$IT = \frac{C_i * IR * ET * EF * ED}{BW * AT} \quad \text{Equation 6-23}$$

Where:

IT	=	the chemical intake (mg/kg-day)
C_i	=	the indoor air concentration (mg/m ³)
IR	=	the inhalation rate (m ³ /day)
ET	=	the exposure time (hr/24hr)
EF	=	the exposure frequency (days/yr)
ED	=	the exposure duration (yr)

BW = the body weight (kg)
 AT = the averaging time (days)

3. To calculate the carcinogenic risk, the intake (IT) or absorbed dose (AD) is applied to the cancer SF for the compound of concern. Accordingly, the risk is calculated as follows:

$$\text{Risk} = \text{IT} * \text{SF} \quad \text{Equation 6-24}$$

Where: Risk = the estimate of health risk (dimensionless)
 IT = the chemical intake (mg/kg-day)
 SF = the contaminant carcinogenic slope factor ([mg/kg-day]⁻¹)

and/or

$$\text{Risk} = \text{AD} * \text{SF} \quad \text{Equation 6-25}$$

Where: Risk = the estimate of health risk (dimensionless)
 AD = the absorbed dose (mg/kg-day)
 SF = the contaminant carcinogenic slope factor ([mg/kg-day]⁻¹)

4. To calculate the non-carcinogenic risk, the hazard quotient (HQ), the intake (IT) or absorbed dose (AD) is applied to the reference dose (RfD) for the compound of concern. Accordingly, the hazard index (hazard quotient) is calculated as follows:

$$\text{HQ} = \frac{\text{IT}}{\text{RfD}} \quad \text{Equation 6-26}$$

Where: HQ = the hazard quotient
 IT = the chemical intake (mg/kg-day)
 RfD = the contaminant reference dose (mg/kg-day)

and/or

$$\text{HQ} = \frac{\text{AD}}{\text{RfD}} \quad \text{Equation 6-27}$$

Where: HQ = the hazard quotient
 AD = the absorbed dose (mg/kg-day)
 RfD = the contaminant reference dose (mg/kg-day)

When there are multiple substances, the sum of the hazard quotients is considered to be the hazard index (HI).

5. The procedures for evaluation of ecological risks will be reviewed on a case-by-case basis.

III. Risk Assessment Report Checklist

A risk assessment report may be a stand-alone document or it may be incorporated into a comprehensive assessment report or Corrective Action Plan. The following format should be used.

1. Executive Summary

A brief and concise overview of information contained in the report. The executive summary should be limited to one to three pages in length and include:

- a. A brief description of the receptors of concern (human, environmental, and water resources)
- b. A detailed site parameter list (refer to **Figure 6-3**).
- c. A summary of the findings, conclusions and recommendations of the risk assessment.
- d. A brief description of the recommended cleanup/closure level(s).

2. Site History

a. Site Description

Include the following (where applicable):

- (1) Site address (street name and number, city, state, and zip code)
- (2) Name of business
- (3) Assessor's Parcel Number (APN)
- (4) DEH File No.
- (5) Property owner (name and mailing address)
- (6) Underground storage tank (UST) owner (name and mailing address)
- (7) UST operator (name and mailing address)
- (8) RP and contact person (name, mailing address and phone number)

b. Current and Past Site Ownership and Activity Record

Provide a chronological list of past and current owners and operators on the site. Include dates of occupancy, a description of the business operations, and chemical usage including handling/storage/disposal procedures.

c. Summary of Current and Future Property Uses

- (1) Provide a summary of on-site use.
- (2) Provide a summary of land usage on all adjacent and nearby properties (including those across the street or alley). Include locations of schools, day care centers, residential areas (including apartments, condominiums, single family residences), hospitals, surface water bodies, and aqueducts within one-quarter mile of the site.

d. History of Past Releases

- (1) Substance(s) released and date
- (2) How release occurred

- (3) Contaminant characterization, including constituents and breakdown products
 - (4) Quantity of substance(s) released (estimate)
 - (5) Location of release on site
- e. Summary of Current and Completed Site Assessment and Remedial Activities
- (1) Summary table of analytical data with sample identification, depth, laboratory test method and results
 - (2) Site maps showing horizontal extent of soil and groundwater contamination (including NAPL plume), probable sources, contaminant migration pathways, surface drainage, subsurface utilities (i.e., water, sewer, electric, gas, telephone, storm drain), boring and monitoring well locations, sample locations, and laboratory test results
 - (3) Site map showing groundwater contour elevations and direction of groundwater flow
 - (4) Cross sections showing vertical and horizontal extent of soil and groundwater contamination, source of contamination, lithology, water table, sample locations, laboratory results, utilities, and well construction
 - (5) Estimated mass of contaminants in soil and/or groundwater
 - (6) Summary of remedial activities conducted to date, including maps, cross sections, mass of contaminants, and discussion of Corrective Action Plan, if applicable
- f. Summary of Near-Term and Long-Term Site Remedial Activities
- (1) Summary of the planned near-term environmental activities (remedial action, monitoring, no action) at the site
 - (2) Summary of the planned long-term environmental activities (remedial action, monitoring, no action) at the site

3. Site Information

a. Regional Geologic Conditions

Summary of the lithology in the site vicinity, as well as any geological features of significance, such as faults, landslides, or variable stratigraphy.

b. Site Geologic Conditions

Description of the soil/bedrock

- (1) Soil properties that may affect the mobility of vapor, water, or contaminants.
- (2) Site features which may influence the migration of contaminants or groundwater through the subsurface, including faults, stratigraphy, subsurface utility lines, abandoned or active wells, geotechnical borings, etc.

FIGURE 6-3
SITE PARAMETER LIST

Soil Parameters	Information Value Used	Reference
Soil Type		
Soil Porosity		
Soil Bulk Density		
Water Content (vadose zone)		
Air Content (vadose zone)		
Water Content (capillary fringe)		
Air Content (capillary fringe)		
Soil Particle Density		
Mass Fraction of Organic Carbon in Soil		
Depth To and Thickness of Contaminated Soil		
Thickness of Uncontaminated Vadose Zone Between Vadose Zone Plume and Groundwater		
Range of Depths to Groundwater		
Capillary Zone Thickness		
Vadose Zone Thickness		
Soil/Water pH		
Hydraulic Conductivity		
Groundwater Parameters	Value Used	Reference
Water Infiltration Rate		
Groundwater Mixing Zone Depth		
Aquifer Dilution Factor		
Surface Parameters	Value Used	Reference
Surface Conditions (paved or landscaped)		
Ambient Air Velocity in Mixing Zone		
Mixing Zone Height		
Contaminated Area		
Width of Contaminated Area		
Thickness of Surficial Soils		
Particulate Areal Emission Rate		
Building Parameters	Value Used	Reference
Foundation Crack Thickness		
Foundation Crack Fraction		
Building Volume/Foundation Area Ratio (res.)		
Building Volume/Foundation Area Ratio (com./ind.)		
Building Vapor Volume Exchange Rate (res.)		
Building Vapor Volume Exchange Rate (com./ind.)		
Depth of Utilities		
Foundation Type		

c. Regional Hydrologic/Hydrogeologic Conditions

- (1) Provide the hydrologic unit, area, and subarea of the site (from the Water Quality Control Plan for the San Diego Region, September 8, 1994).
- (2) Describe surface drainage and water bodies.
- (3) Discuss historical low and high groundwater levels as well as any recharge/discharge areas within the basin. If multiple aquifer systems are present and known, describe the geometry and distribution of the aquifers. Note the regional groundwater flow direction.
- (4) Indicate current or potential beneficial uses of groundwater in the site vicinity.
- (5) Note any potential or pending changes in groundwater use.

d. Site Hydrogeologic Conditions

- (1) Present a detailed description of the aquifer system(s) beneath the site, including perched groundwater, the capillary fringe zone, and the saturated zone. Provide a detailed description of the aquifer lithology. Any aquitards and aquicludes that could influence the migration of subsurface contaminants should be noted.
- (2) Describe groundwater elevation, flow direction, and gradient. Determine whether off-site activities may be influencing flow direction or gradient. Note any on-site or near-site recharge areas.
- (3) Provide a summary of any physical properties (grain-size, permeability, etc.) and aquifer tests.
- (4) Provide available estimates for hydraulic conductivity, velocity, or other aquifer characteristics.
- (5) Provide an evaluation of the current and probable future use of the surface and groundwater resources around the site.

e. Summary of Site Meteorology

- (1) Prevailing wind direction.
- (2) Average annual rainfall, temperature, etc.

f. Well Inventory Survey

Include a summary of all nearby wells (within one-quarter mile of the source) and plot them on the site map. Identify the well screen interval versus the subsurface zone of soil contamination at the subject site, and whether a well is currently impacted, potentially impacted, or not anticipated to be impacted.

4. Compounds of Concerns (COCs)

The report should discuss the rationale for including or excluding potential COCs as well as a summary of the parameters used in the evaluation.

a. Site Contaminants

Discuss all reported contaminants on-site.

b. Table of COCs

Provide the physical characteristics and degradation aspects for each COC in a table format.

(1) Physical Characteristics:

- Solubility
- K_{oc}
- K_{ow}
- Vapor Pressure
- Molecular Weight
- Molecular Formula
- State at Room Temperature
- Oxidation/Reduction Potential
- Density (liquid/vapor)

(2) Degradation Compounds

- Degradation products
- Half life of products (provide reference)

c. Toxicity Assessment

(1) Carcinogenic

- Identify and list the cancer SF for each COC in a table

(2) Non-Carcinogenic

- Identify and list the RfD for each COC in a table

5. Exposure Assessment

The exposure assessment is divided into two sections. One is identification of human and environmental exposures, and the other is the protection of groundwater and surface water as a resource.

The purpose of the exposure assessment is to identify human and environmental populations exposed to contaminants, or the impacts to groundwater and surface water, and identify the pathways through which they would be potentially exposed or impacted.

a. Potential Receptors

(1) Humans and environmental populations

Describe the populations on or near the site. Identify the prevailing wind direction and direction of groundwater flow. Include the population locations, activity patterns, and the presence of sensitive subgroups (e.g., children, elderly people) within one-quarter mile or farther if potential exposure to contamination extends beyond one-quarter of a mile.

(2) Groundwater and Surface Water Resources

Describe the existing and potential beneficial uses of the groundwater and surface water at and near the site.

b. Exposure Pathway Analysis

An exposure analysis includes identification of potentially complete exposure pathways. An exposure pathway is complete if four elements are present:

- A source and mechanism of a chemical release to the environment (e.g., contaminated soil releases of chemicals by volatilization);
- An environmental transport medium (e.g., groundwater, surface water, air, soil or subsurface utilities);
- A point of potential contact between the receptor and the contaminated medium (the exposure point); and
- An exposure route at the contact point (e.g., inhalation, ingestion).

Based on the exposure analysis, summarize complete exposure pathways for the site using current and future anticipated land use.

c. Exposure Concentrations

Provide the exposure concentrations of COCs at the exposure point for completed pathways.

(1) Direct Use of Monitoring Data

Use of monitoring data to estimate exposure concentrations typically is applicable to the following potential exposure points (current use):

- Direct contact with contaminated soil or surface water (e.g., use 95% upper confidence level [UCL] concentration of soil or surface water concentrations in vicinity of likely exposure point).

- Drinking water (contaminated ground water and/or potable municipal water) piped through a zone of contaminated soil (e.g., use the UCL concentrations of the last four quarters of groundwater monitoring data from each well located within the plume).
- Direct use of the soil vapor concentrations as described in [Section 5.VI](#). Use the 95% UCL concentration in soil gas measurements that are representative of the area of contamination.

(2) Fate and Transport Modeling

A combination of monitoring data and environmental fate and transport modeling may be used to estimate exposure point concentrations that vary temporally or spatially. Examples of where fate and transport modeling is used are:

- Future concentrations in contaminated groundwater that will be used for drinking water;
- Future concentrations in contaminated groundwater that may volatilize to the surface;
- Current air concentrations (indoor, outdoor, and offsite) from volatile chemicals in soil, shallow groundwater, and surface water; and
- Estimated concentrations in fish biota that uptake chemicals from water, sediment, or soil.

d. Estimated Intakes

Pathway-specific intakes are dependent on three types of variables:

- Chemical-related variable-exposure concentrations (chemical concentrations in media at exposure point);
- Variables that describe the receptor (e.g., exposure frequency and duration, and body weight); and
- Assessment-determined variable (e.g., averaging time of exposure based on land-use and activity patterns.

For non-carcinogens, the averaging time (AT) is generally over limited exposure duration. Non-carcinogenic intakes are referred to as the Chronic Daily Intake (CDI). For carcinogens the AT is over an individual's lifetime, assumed to be 70 years. The intake for a carcinogen is referred to as the Lifetime Average Daily Dose (LADD).

e. Risk Characterization

Carcinogenic risk

Determine the corresponding carcinogenic risk for each contaminant in each complete exposure pathway and the cumulative cancer risk for each exposure pathway. The acceptable risk is considered by DEH to be less than 1×10^{-6} (i.e., one theoretical excess cancer in a human population of one million).

Non-carcinogenic risk

Determine the corresponding hazard quotient for each contaminant in each complete exposure pathway. It is appropriate to sum the hazard quotients of compounds with similar toxicological endpoints. The sum of more than one hazard quotient is the hazard index. The hazard index for more than one substance or the hazard quotient for a single substance must not exceed a value of 1.0.

f. Cleanup/Closure Levels

Where applicable, calculate the cleanup/closure levels to achieve acceptable risk for cumulative exposure pathways.

6. Uncertainty

Discuss the uncertainties that have a bearing on contaminant fate and transport models used, the calculation of risk and the degree to which the uncertainty may tend to underestimate or overestimate the actual risk.

Frequently, the final values presented are very conservative. They may be based on the upper 95th confidence interval or the “maximally exposed population.” The “median value of excess” cancer risk may likely be several orders of magnitude lower. On the other hand, sensitive populations such as the elderly and children may be prone to higher rates of toxicity or cancer than the population at large. Identify the key site variables and assumptions that contribute most to the uncertainty. The end result of a risk assessment is a qualitative/semi-quantitative assessment that is useful to risk managers in evaluating and ranking risk—not determining absolute risk.

7. Findings, Conclusions, and Recommendations

Summarize the findings and conclusions. Provide recommendations for cleanup/closure levels. A registered professional must sign the final risk assessment report. Generally, this work requires geologic evaluation and interpretation, and the qualified professionals who have expertise in this field are Registered Geologists and Registered Civil Engineers. If values other than default values are used to calculate exposure and risk, the report will also need to be signed by a Certified Industrial Hygienist (CIH) or a Diplomate American Board of Toxicology (DABT).

IV. RISK MANAGEMENT

DEH's role is to review the assumptions, calculations, and conclusions presented in the risk assessment and evaluate the risk management decisions proposed by the RP/consultant.

DEH requires risk management decisions be made if the risk assessment indicates an unacceptable level of risk. Examples of some risk management decisions are:

- Removal and/or treatment of contaminants,
- Creation of barriers to block migration or exposure pathways, or
- Other engineering controls to reduce or prevent exposure.